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Radiation-Induced Noise Response of the Jaycor MPC-8 Radiation-Hardened Current Probe

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13. ABSTRACT *(Maximum 200 words)*

This report presents the response of the MPC-8 current probe to pulsed radiation. The MPC-8 is a miniature (0.15 × 0.2 in.) balanced inductive current probe which has a relatively low noise response to radiation. The small size and considerable radiation hardness have caused it to be widely used in investigations of radiation response of electronics and also in fundamental studies of radiation-driven charge emission/collection from materials. The finding is that there is considerable variability among probes, not all of them having the desired low radiation sensitivity. In situations where the probe is exposed to pulsed electric fields, its response is much greater than expected; it apparently must be protected by an external Faraday shield.

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Executive Summary

A test program was undertaken to determine the radiation-induced noise response of a balanced inductive current probe, the MPC-8, designed by JAYCOR. Its small size and reputation for low noise response to radiation have made the MPC-8 a natural choice for pulsed radiation tests of electronics, such as the JADE (Joint Army/Defense Nuclear Agency Experiment) computer boards. In these types of tests a conductor carrying the current to be measured is passed through the probe, and the output of the probe, proportional to the current, is monitored on an oscilloscope.

In both underground tests (UGTs) and aboveground tests (AGTs) of the JADE circuit, anomalously large current probe signals were seen. In fact, during AGTs at the Double Eagle simulator, outputs equivalent to several milliamps were seen from background noise current probes, although these probes had no current-carrying conductor passed through them and therefore should not have reported a signal. Large signals were also seen during UGTs, but it was thought that other factors, such as long cable runs and complex instrumentation, might have influenced the results. It now appears that probe noise response likely was the source of the excessive current signals seen in the UGT.

The MPC-8 current probes were tested at HDL's High-Intensity Flash X-Ray (HIFX) facility by exposing them to a well-defined beam of HIFX radiation and recording the output signal on an oscilloscope. The probe was exposed in several different orientations, several electrostatic shielding configurations, and with and without lead shielding. Every effort was taken to reproduce the test situation. During the tests in the HIFX pulsed x-ray source, the probes showed considerably greater noise than expected. The most noisy probe showed a radiation-induced response equivalent to 3.6 mA at a normalized dose rate of 1×10^{10} rads(Si/s). The tests also demonstrated that the probe was sensitive to externally applied electric fields and that improvement was required in the probe's Faraday shield. These findings have led to a redesign program at JAYCOR for this widely used probe.

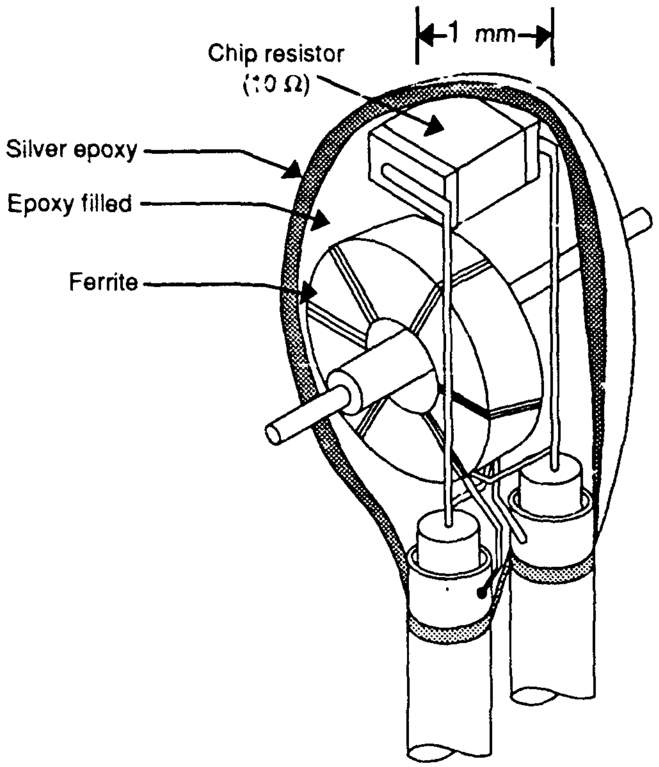
1. Introduction

This report presents the procedures and results of a test program to determine the source of the radiation-induced noise response in MPC-8 current probes developed by JAYCOR; our objective is to reduce that noise. The probe, developed by JAYCOR, is a natural choice for pulsed radiation tests of electronics, such as the JADE (Joint Army/Defense Nuclear Agency Experiment) computer boards. In such testing, a conductor carrying the current to be measured is passed through the probe, and the output of the probe, proportional to the current, is monitored on an oscilloscope. The tests reported herein were undertaken to find an explanation of anomalously large current probe signals seen in aboveground tests (AGTs) and underground tests (UGTs) of the JADE circuit. In particular, in AGT tests at the Double Eagle simulator, outputs equivalent to several milliamps were seen from background noise current probes.[1] These probes had no current-carrying conductor passed through them and consequently should have reported no signal. Unexplainably large signals were also seen in the UGT testing, but here the long cable runs and complex instrumentation system made it more likely that factors other than the probes' own noise response might be involved. (In retrospect, it appears that probe noise response likely was the source of the excessive current signals seen in the UGT.)

The MPC-8 current probe is shown in figure 1. Its essential part is a ferrite core with a balanced bifilar coil winding. The current to be measured is carried on a wire passed through the ferrite core. This current produces a magnetic field which is coupled into the windings, producing a proportional balanced voltage output on the two copper-jacketed (cujac) cables. A 10-ohm shunt resistor extends the frequency response beyond that which would be attained if the probe connected directly to the 100-ohm load provided by the balanced 50-ohm cujac cables. The coil connections and resistor are insulated by a coating of epoxy and then the entire probe, including the ends of the cujac cable shields, is covered by a layer of highly conducting silver epoxy. The Faraday shield formed by the conducting epoxy is broken only by tiny holes for passage of the wire being monitored. The small physical size and balanced winding structure of this probe provide a relatively low value of radiation-induced noise when the probe is placed in a pulsed radiation environment. The noise level was originally reported as a signal equivalent to 6 mA at 10^{12} rads(Si/s).

[1]James C. Blackburn, Dale M. Robertson, Gregory K. Ovrebo, and Steven M. Blomquist, *Disko Elm Active Electronics Experiment, Project Officer's Report, Vols I and II*, HDL-TR-2175 (July 1991) and -2175S (to be published).

Figure 1. MPC-8 current probe: Probe is about 4 × 7 mm, with a bifilar-wound secondary providing a differential output. Electrostatic shielding is provided by a thin outer coating of conducting silver epoxy.



When tested in the High-Intensity Flash X-Ray (HIFX) pulsed x-ray source, the probes had considerably greater noise than expected; the most noisy showed a response equivalent to 3.6 mA at a normalized dose rate of 1 x 10^{10} rads(Si/s). This finding, along with our suggestions for the source of the noise, has led to a redesign program at JAYCOR for this widely used probe. Vanderwall[2] used similar testing techniques at HIFX to provide data for optimization of the coaxial probes used in the low-noise test apparatus recently built by JAYCOR.[3]

2. Test Apparatus and Procedure

The concept and execution of the tests were straightforward: we exposed the probe under test to a well-defined beam of HIFX radiation (pinched beam, photon mode), and the output signal was recorded on an oscilloscope. In order to delineate the nature of the response as well as its amplitude, the probe was exposed in several different orientations, several electrostatic shielding configurations, and with and without lead (Pb) back-shielding. A Pb back-shield had been used in the JADE board cassette and therefore was needed to reproduce that

[2]Jonathan Vanderwall and James C. Blackburn, *HIFX Testing of Pogo Voltage/Current Probes*, Harry Diamond Laboratories, Technical Letter 491-3 (circulated from the TRE-SGEMP Branch, HDL) (April 1991).
[3]W. A. Seidler et al, *The Development of a Low-Noise Parts Test Facility at HIFX*, presented at the 1991 Heart Conference and submitted for publication in the J. Rad. Eff. Res. and Engr.

test situation, where the noise problems of the probe were originally identified. In addition to the radiation testing, the conductivity of the shield-covering of the probe was measured.

Care was taken to ensure that the desired quantity, the response of the probe head, was measured uncontaminated by the response of interconnecting cables, etc. To this end, we observed good instrumentation practices; e.g., doubly shielded balanced lines and high rejection baluns (balanced-to-unbalanced line transformers) were used and background noise was measured in a variety of ways to ensure that these measures were successful.

Figure 2 is a schematic of the measurement system electronics. A double layer of high-density copper braid shielding covers the length-matched solid copper-walled coaxial cables (cujacs). This shield is firmly grounded to the shield-room inner wall and extends either over the probe head or to the Pb shielding block (when the Pb is used; see fig. 3). The balun is inside an oscilloscope plug-in which fits into the Tektronix 7104 recording oscilloscope. The use of a plug-in rather than a separate balun avoids any susceptibility to noise due to common-mode currents on the unbalanced line between the balun and the vertical amplifier. A delay-line, also a plug-in to the 7104, allowed us to capture the full signal even though we were triggering from the radiation pulse; timed electronic triggering of HIFX was not necessary.

2.1 Probe Test Without Pb Backing

Figure 4 shows the exposure configurations for the probe when the Pb backing was not used (results with Pb are shown later). The probe was contained in an overall shield braid which was insulated from the

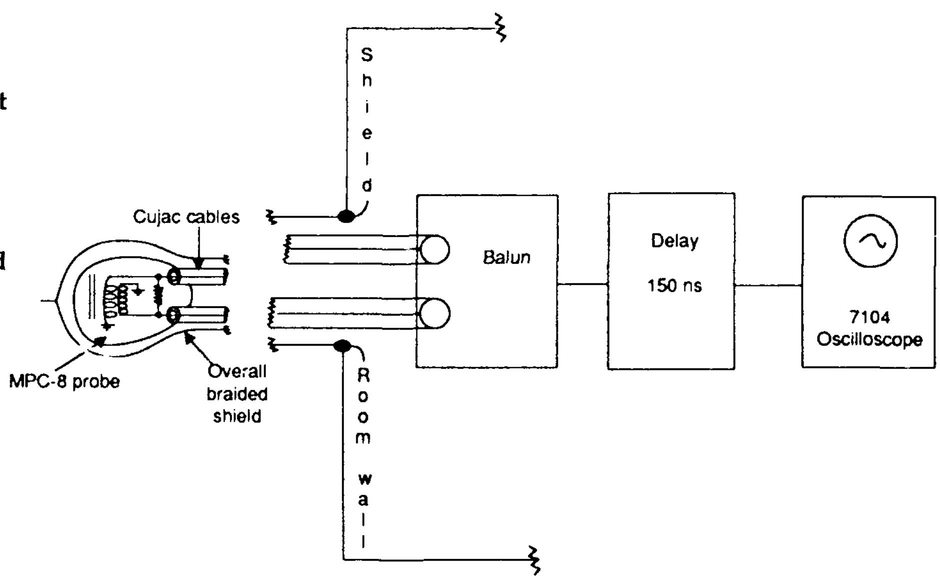
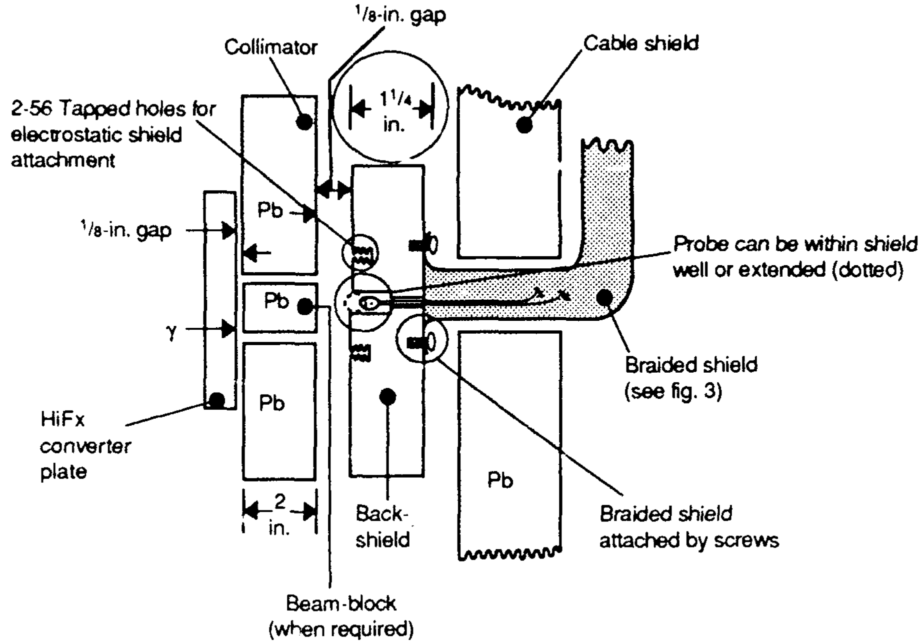


Figure 2. Measurement electronics: Cujac cable and probe are covered by a continuous double-braid shield, grounded to shield-room wall. Balun and delay line are plug-ins integral with oscilloscope.

Figure 3. MPC-8 current probe with Pb back-shield. Beam-block is inserted for background noise measurement.



probe head by a plastic tube (as shown) for some measurements and grounded to the probe head in other measurements. The entire probe and shield assembly was then rotated about its axis to provide four directions of irradiation. To determine cable noise the assembly was translated relative to the beam (bottom of figure) so that only the cable was irradiated. In this "cable-only" test, since the length of cable irradiated was greater than that exposed when the probe head was irradiated, it provided a worst-case estimate of cable noise. Tests were also made with the Pb bricks closed together; the observed signal was approximately zero, as it should be. The results of these tests are summarized in tables 1 and 2 with representative traces shown in figures 5 and 6.

Table 1 presents the results when the probe was electrostatically shielded by, but not grounded to, the overall braid. It is seen that for different probes the response varies over more than an order of magnitude. Probe 151 has the least response, approaching that of the cable alone. It is surprising that the polarity of the probe output does not change as the probe is rotated in the radiation beam. This fact means that the noise signal is not a result of the unavoidable differences in radiation conditions within the probe (e.g., one structure shielding the one behind it, or the directivity of knock-off electrons), but rather to some fixed asymmetry such as a bubble in the dielectric coating. The fact that the polarity retains the same sense relative to the lead wires (except for probe 165) suggests that the asymmetry is a fixed feature of the construction. For example, within the probe the positive lead wire is perhaps shorter than the negative lead. A low radiation response requires a symmetric and balanced structure.

Figure 4. Experimental setup for irradiation at HIFX. Shielded probe is rotated and translated with respect to radiation beam to provide several types of exposure. For system background noise, probe is at 0° position with collimator closed.

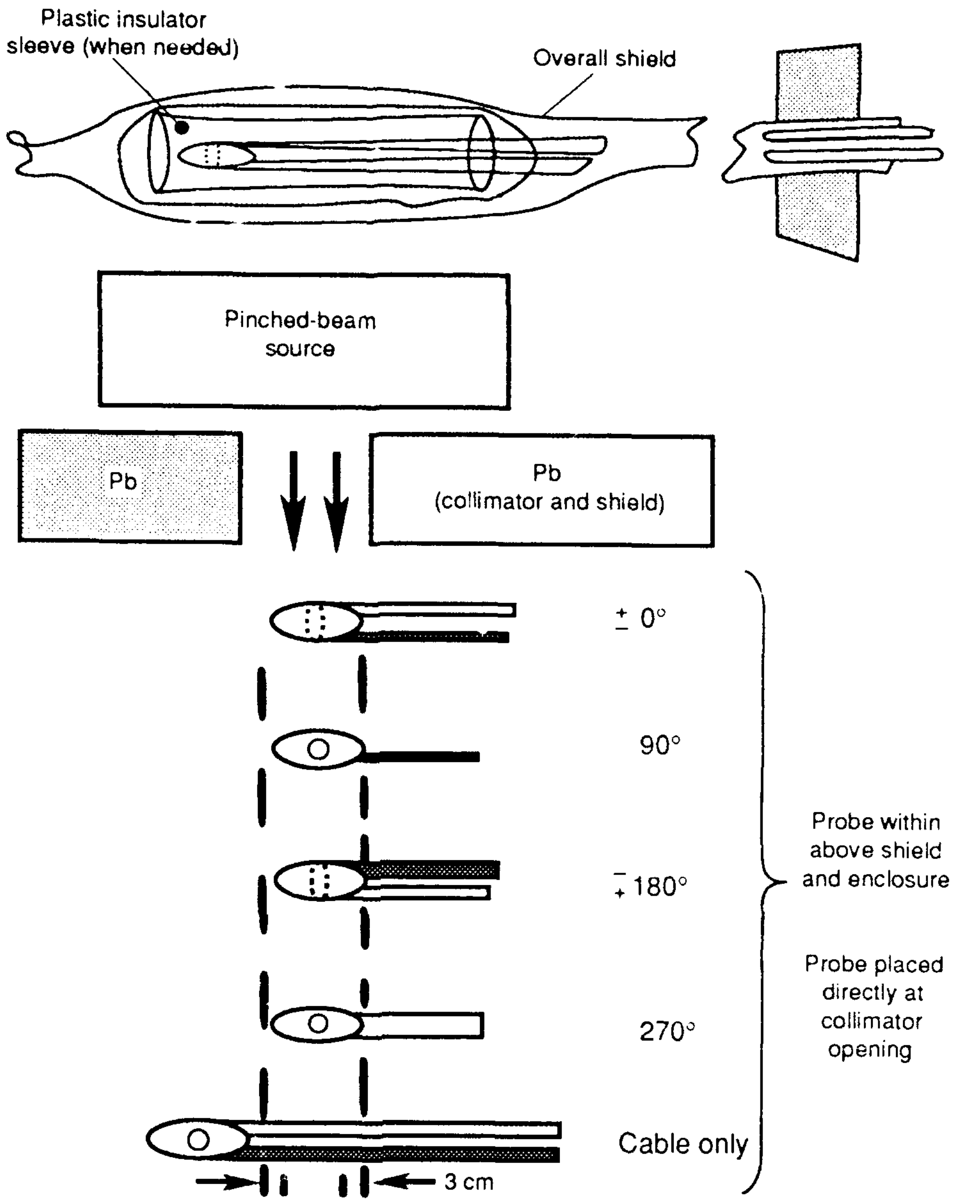


Table 2 shows the results of further testing of a noisy probe (177). In particular, we wanted to see whether grounding the overall shield braid to the probe head would substantially decrease the noise response below that with the shield covering, but not grounded to, the probe head. The finding was that grounding reduced the response somewhat, but the radiation-induced noise was still excessive. As in table 1, the signal polarity remained the same, decreasing in amplitude when the probe was rotated 90°. No measurements were made without an overall shield because in this phase of testing we wanted to measure only the probe's direct radiation-induced response.

For the last entry in table 2 ("Double outer shield"), a second 3/16-in.-diam shield braid was pulled over the probe and its 0.035-in. cujac cables; this shield and the probe were placed inside the larger shield braid used in previous shots. Both shields and the cujacs were bonded together a few inches from the probe head. We saw no additional reduction in signal with this form-fitting inner shield (which continuously contacted the probe head and cables). When the probe output was displayed on two separate oscilloscopes, one connected to each cujac, we found that the output was differential (equal in value, opposite in sign), as it should be.

Table 1. MPC-8 current probe outputs vs. orientation relative to radiation incidence (see fig. 4). "Cable only" and "Beam blocked" refer to system noise measurements discussed in text. Current probe noise output (mA) normalized to 1 × 10[10] rads(Si)/s

Probe number	Orientation to fluence 0	90	180	270	Cable only	Beam blocked
151 (least noise)	0.2	~0.2	—	—	—	~0
166 (most noise)	3.6	2.5	—	—	—	—
150	0.4	0.4	0.7	—	0.3	~0
157	0.7	0.8	—	—	0.2	~0
159	1.4	1.0	—	—	—	~0
165	-0.9	-1.1	—	—	—	—
170	0.4	~0	0.6	—	—	—
177	2.6	1.8	1.8	1.8	—	—
185	1.8	1.0	—	—	—	—
198	2.6	2.6	—	—	—	—

Table 2. MPC-8 current probe No. 177 output vs orientation and electrostatic shielding. These data are a detailed study of the response of a noisy probe

Orientation	Shield	Output (mA, normalized to 1×10^{10} rads(Si)/s)	Beam blocked
0°	Not grounded to probe	+1.8	No
0°	Not grounded to probe	<0.1 mA	Yes
0°	Shield grounded to probe	+1.0 mA	No
0°	Not grounded to probe	+1.8 mA	No
0°	Shield grounded to probe	+1.1 mA	No
0°	Shield grounded to probe	+1.0 mA	No
90°	Shield grounded to probe	+0.7 mA	No
90°	Shield grounded to probe	<0.1 mA	Yes
0°	Double outer shield grounded to probe	+1.0 mA	No

Figure 5. Response of probe 177 (the most noisy) at four rotational positions (as shown in fig. 4). Note that polarity of signal remains the same.

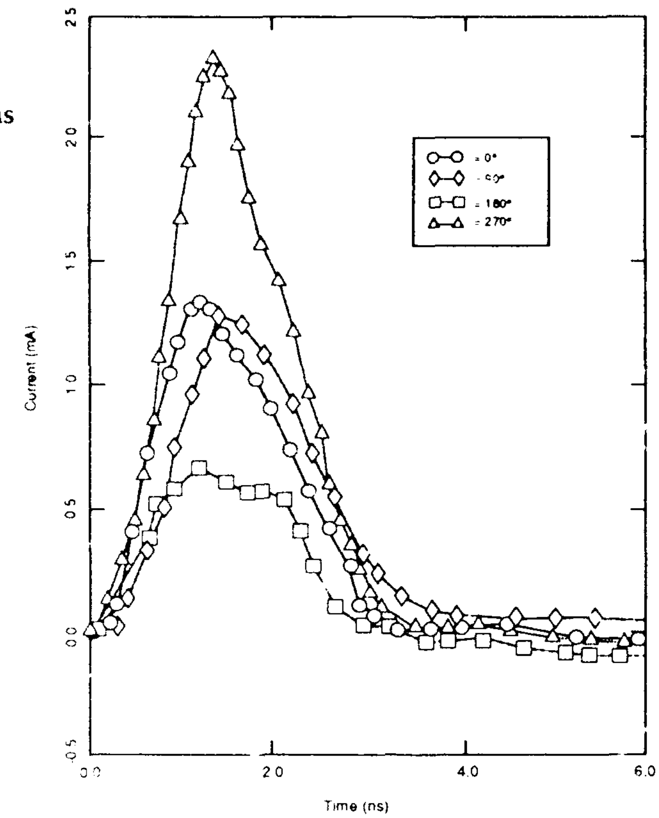
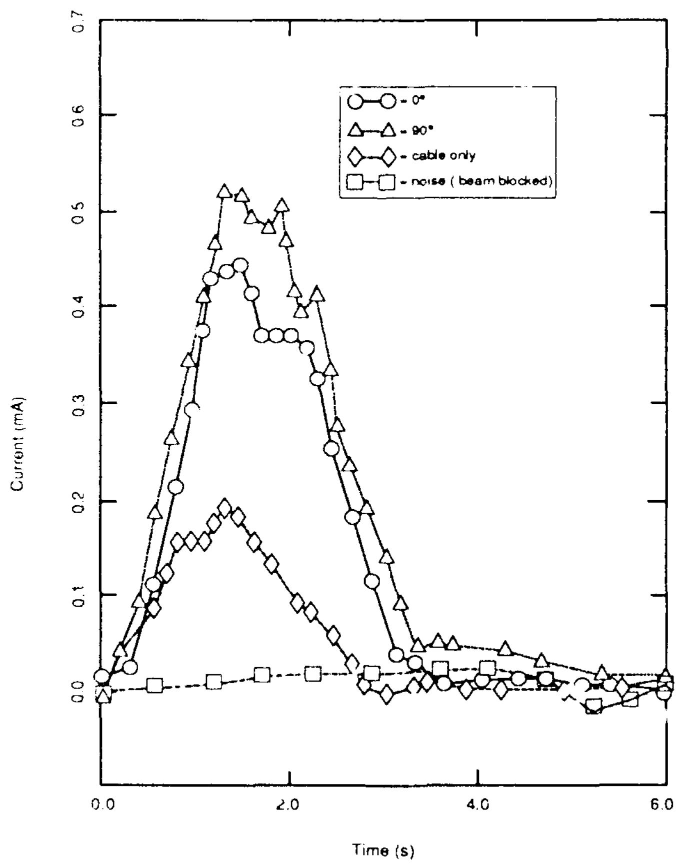


Figure 6. Probe response and background noise for probe 157 (one of the least noisy). Even for this quiet probe, the response is several times the cable-only response and much greater than background.



It has been a surprising result of these tests that the output from the probes is always differential. At the outset, we had expected that noise response would be highly unequally divided between the probe outputs. As part of the explanation for the equality, consider the bifilar coils of the probe as the primary and secondary of a transformer. It is apparent that there will be a tendency for a signal applied to only one of the two windings to be coupled inverted into the other winding. It is not true, however, that the effective ratio is 1:1 because the current through the 10-ohm resistor is in the same phase (not inverted) as any current through the driving winding and thus subtracts from the current from the driven winding.

2.2 Probe Tests With Pb Backing

One of the primary motivations for this investigation was our desire to explain the large radiation-induced noise signals seen in the background current probes of the JADE test boards, which, according to accepted practice, were attached to the back of the JADE circuit board and fitted into recesses ("wells") in the Pb shield behind the boards. The probe head, itself shielded by a covering of conducting silver-epoxy (see fig. 1), was bonded to the board ground by silver-epoxy. This bonding epoxy layer was thin and about 4 mm^2 in area, providing good conductivity. The Pb shield was coated with plastic to reduce emission, but in retrospect we see that the ~0.003-in. coating was marginal. The surface of the Pb was spaced from the board by about 0.150 in. to clear the soldered connections on the board and the board coating. This configuration was approximately duplicated in the HIFX tests. Figure 3 depicts this experimental setup. Probe 177, the one having greatest noise response in the previous tests, was used in all the Pb-backed testing. The Pb block was slit through the plane containing the cujac holes so that it could be closed around them; this permitted us to insert the probe without removing the connectors on the cujacs. The center hole was deep enough (about 7 mm) so that, when desired, the tip of the probe could be placed within the plane of the surface of the Pb. The probe could also be moved so that its tip protruded from the Pb by a few millimeters; this corresponded to the probe's location on the JADE boards. Various grounding/shielding structures were placed over the probe and in front of the Pb. In all cases, the exterior shield braid was firmly attached to the back of the Pb block, and additional Pb bricks shielded the cables.

The first testing with the Pb back-shield was in one of four configurations: (1) probe within well (probe head flush with surface), (2) probe extending ¼-in. from well, and (3) and (4) a repeat of (1) and (2), but with a 1-¾-in. Pb beam-block placed in the collimator opening. The block was inserted or removed without moving or touching the probe and cable assembly.

Figure 7 shows the results of this test in representative traces for the four conditions mentioned above. It is seen (7(a) and (b)) that the probe response is small when the probe head is within the shielding well—even less than when the probe is irradiated side-on (see fig. 5). The noise signal in 7(a) has more high-frequency content than seen in figure 5. It also contains a slowly varying component with a time period of about 120 ns. This component appears in all the traces where the probe is irradiated in the Pb back-shield. Perhaps it results from the poorer radiation shielding of the cable near the probe head in this configuration.

Figures 7(c) and (d) show a very large noise signal when the probe protrudes from the Pb, rather as it did on the JADE boards. More surprising is that in figure 7(d) (beam-block in place), the signal

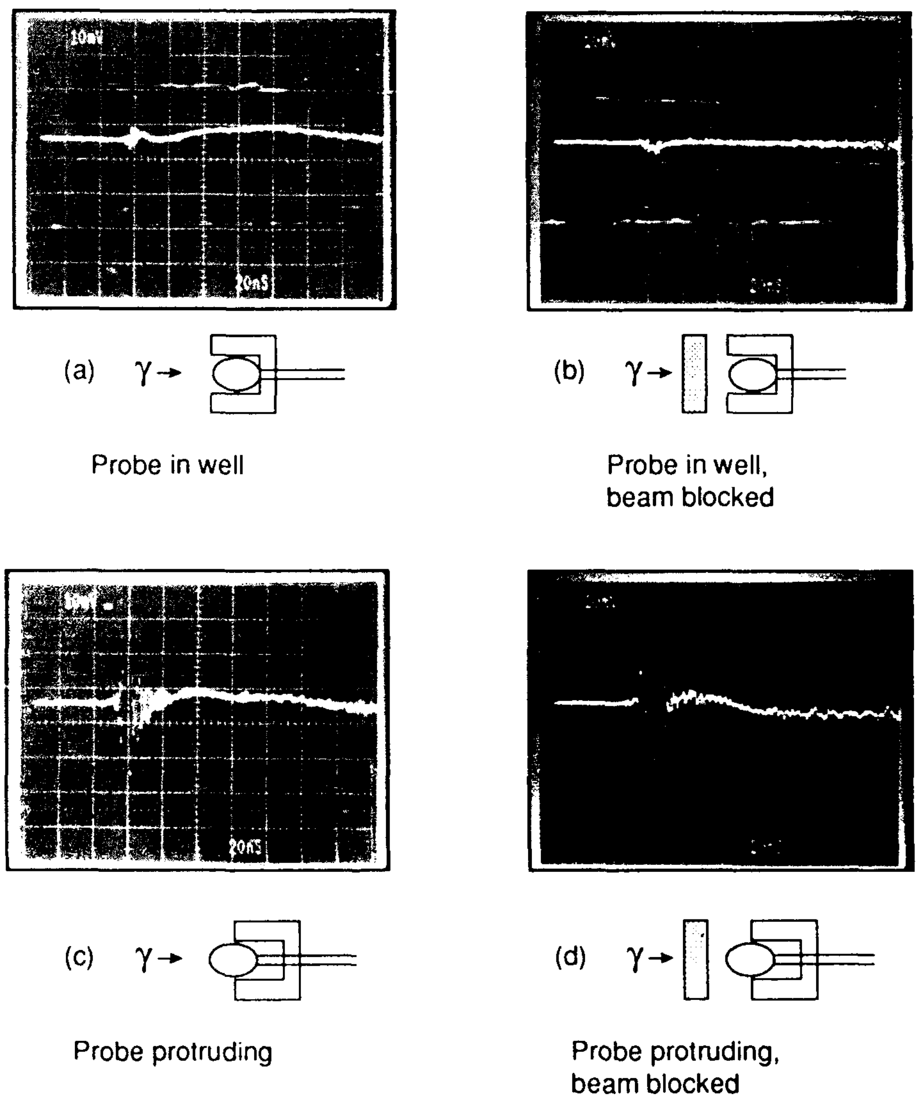


Figure 7. Test results with probe in back-shield assembly of figure 3.

amplitude is not reduced, although perhaps the high-frequency content is.

The previous configurations are a rather inaccurate reproduction of the JADE situation in that no grounding connection is made to the probe head. In the next tests, various grounding and electrostatic shielding methods are employed to better mimic the JADE situation. Figures 8(a) through (g) exhibit results with the probe head protruding, but attached to the front of the Pb enclosure by a single strip of conducting copper tape, with and without the beam-block.

Figure 8(a) is the response with the irradiated probe protruding ¼ in. This is the same condition as figure 7(c), and the traces are reasonably similar. In trace 8(b), the protruding probe head is grounded to the front of the Pb enclosure by a single strip of conducting tape. The signal decreases to nearly its value in figure 7(a), where the probe was within the Pb well. Surprisingly, once again when the beam-block is in place (fig. 8(c)), the signal does not decrease; it is slightly larger, although (as before) the lower frequency (~120 ns) component vanishes. In trace 8(d), the copper tape spans the opening in the Pb, but it does not contact the probe head, being insulated from it by thin plastic tape. There results a considerable increase in signal. When the beam-block is removed (fig. 8(e)) the signal is reduced, as has been observed in the previous test.

Figures 8(f) and (g) show the result when the protruding probe is better electrically shielded than in 8(d) and (e); the probe is now completely covered by four strips of copper tape. The strips are insulated from the probe head, but do provide a tight electrostatic shield of the probe (consider that in the previous test, with a single strip of tape, a gap exists transverse to the axis of the tape). Now the beam-block reduces the signal, and even when the beam-block is not present (fig. 8(g)) the noise level is comparable to the side-on tests reported in section 2.1.

From these results, it is evident that the probe has considerable sensitivity to external electromagnetic fields: placing it within an effective electromagnetic shield (as in fig. 8(f)) reduces its response to levels approximating the earlier side-illuminated tests. Apparently the major noise problem is not radiation drive to the probe but external electric (magnetic) fields coupling into it. This effect was not detected in the earlier tests because it was then assumed that the problem was solely direct effects of the radiation, and all tests were made with the probe covered by an effective electromagnetic shield.

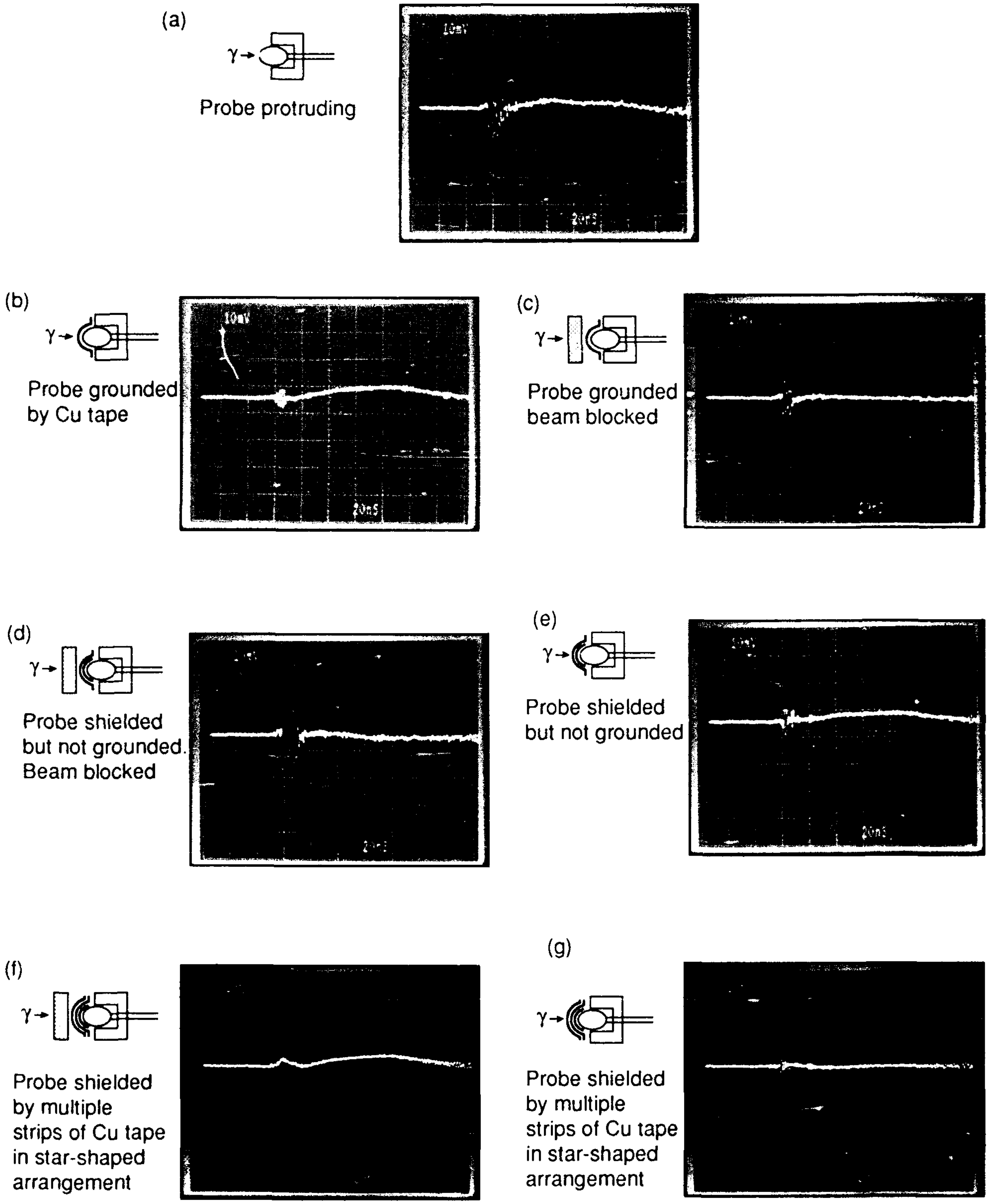


Figure 8. Results with probe in back-shield assembly and grounded and/or shielded by copper tape. In 8(f) and (g), multiple strips of tape provide excellent electrostatic shield.

To finish the investigation into probe noise susceptibility, two more sets of data were measured: (1) tests similar to those just outlined, but with shields more effective than copper tape and (2) measurements of the resistivity of the external (shielding) coatings on two probes. Here the shielding was provided by a 6-mil-thick by 3/4-in.-wide copper strap. The copper was either flat or U-shaped depending on whether the probe was within or protruding from the Pb. The strap was grounded to the Pb by 4-40 screws and connected to the probe head with a 1/8-in.-long flat-head 2-56 screw bonded to the tip of the probe head by a highly conducting epoxy (Epo-Tek 410), with a resistivity of about 3 x 10^{-4} ohm-cm. This epoxy is similar to that which covers the probe itself.

Figures 9(a) and (b) compare this probe response with the irradiated probe protruding from the Pb (fig. 9(a)) and with the beam blocked (fig. 9(b)). Again, the result is that inserting the beam-block increases the noise response. Our explanation for this surprising result is that knock-off electrons create an intense field in the narrow space (~1/4-in.) between the rear surface of the Pb beam-block and the surface of the Pb in which the probe is located, and that this field couples into the probe through its shield coating.

Figure 9(c) is the probe configuration of figure 9(a) (no beam-block, probe protruding), but now with the U-shaped copper strip installed: the response is little different from figure 9(a). When the beam-block is inserted (fig. 9(d)), the response increases. For figure 9(e), the U-strap is rotated 90° relative to the probe's orientation in figure 9(c). No appreciable difference is seen; apparently the axis of the field penetrating the opening of the U-strap relative to the probe's ferrite core is not important.

In figures 9(f) and (g), the probe is within the well and a flat copper strap closes the opening and joins the probe to the Pb. The response is now similar in every respect to the side-on irradiation results where the probe was electrostatically (and magnetically) shielded by braid. Again, it appears that electromagnetic noise effects are even more pronounced than direct radiation drive.

Finally, the resistance of the probe coating was measured at several points as depicted in figure 10. It is seen that the noisy probe (177) has 2 to 3 times the coating resistance of the "quiet" one (155). We obtained the measurements by drawing a constant 0.1-A current between cujac and screw and measuring the voltage drop at the locations indicated using a sharp-pointed probe.

Figure 9. Bolted copper strap used to provide firm grounding connection. In 9(e) the copper strap is rotated 90° relative to its position in 9(d).

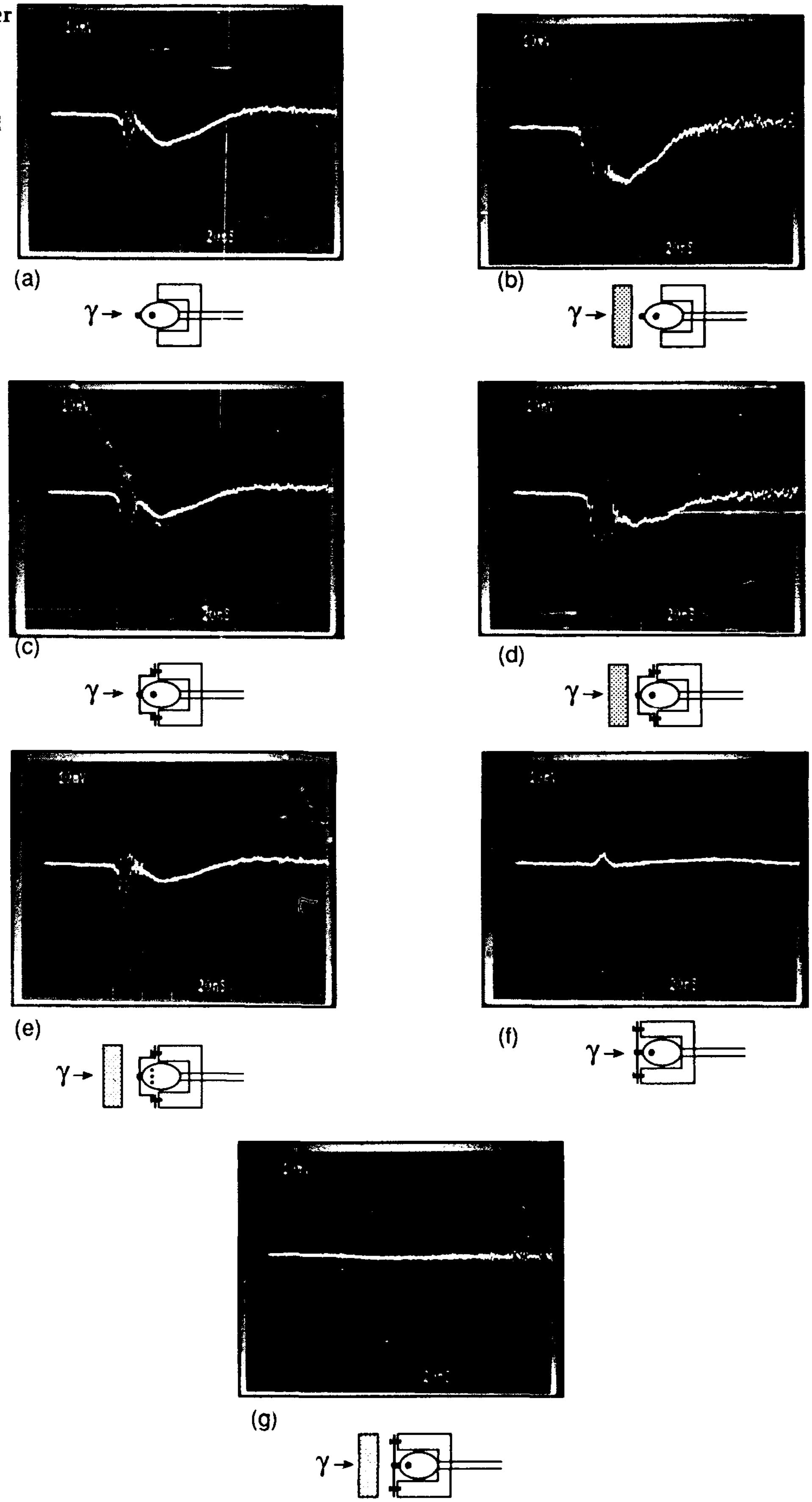
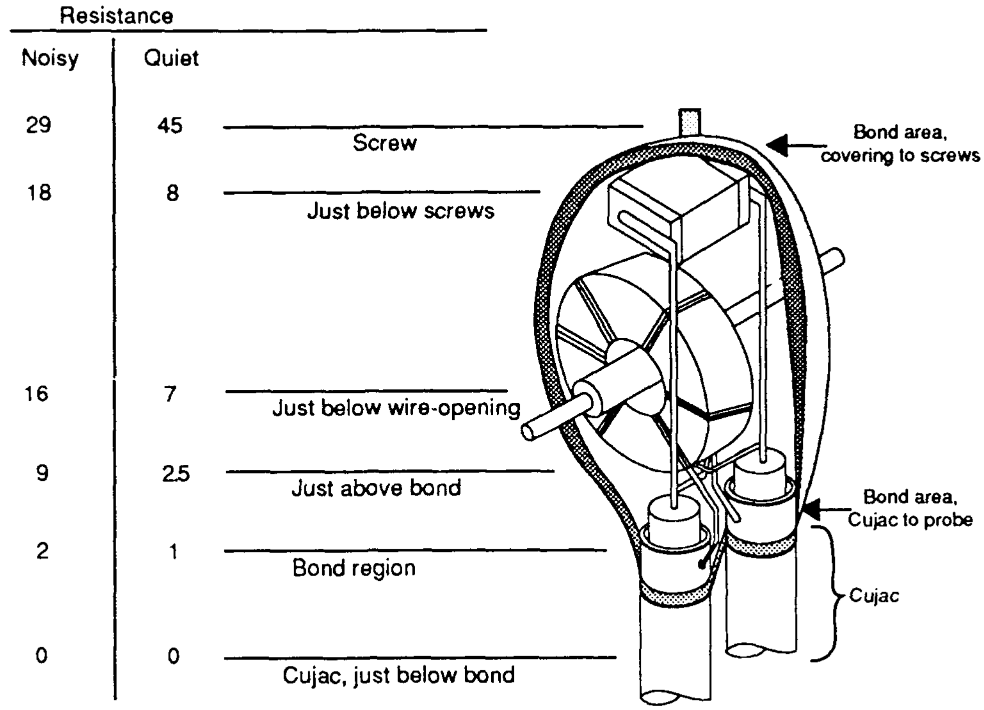


Figure 10. Measurement of resistance of conducting epoxy covering of noisy probe (left) and quiet probe (right).



Pulse current-injection tests were also made on both the noisy and the quiet probes. For this, the probe was arranged so that its leads were parallel to a ground plane, and a fast-rise pulse was injected through the 2-56 screw. The probe's output was viewed both through a balun (thus displaying the difference between the + and – leads) and through each lead separately. The results were extremely noisy, with the + and – leads not being of any discernible relative phase. Further, there was no clear distinction between the quiet and noisy probes. Such a current injection approach does not appear suitable as a screening procedure.

3. Summary and Recommendations

This investigation has shown that there are at least two partially separate reasons for the undesirable radiation-induced response of the MPC-8. One is the direct radiation-induced response, which is best seen in the results of the initial tests with a side-on illumination of the probe. This result was little affected by other parameters as long as external electromagnetic effects were shielded by an external braided shield (or shields). The fact that the magnitude of the response changes relatively little as the probe is rotated in the radiation beam tells us that the response is not a result of differential shielding (of one part of the structure by another) but rather due to some probe asymmetry. The constancy of the polarity of the response from probe to probe suggests that it is likely some feature associated with one lead or coil winding—perhaps just a slightly longer lead or larger solder bond. The constancy suggests it is not something as random as a bubble. Perhaps magnified photos should be made of future assemblies before they are coated with epoxy; some correlation might be found between some small feature and the noise response.

The second reason for the probe response is a sensitivity of the probe to electric fields when it is not externally shielded. This sensitivity suggests that the shielding effectiveness of the conducting epoxy is inadequate. In response to our findings, JAYCOR has suggested that electroplating is likely to be a satisfactory method of constructing an adequate shield on this small irregular surface.

The nature of the response seen in the Pb-backed tests (without an external Faraday shield) looks quite like that seen on the background probes on the JADE board: it has a great deal of high-frequency content and its detailed shape is not predictable. This result appears to identify the source of the excess current probe noise seen in the JADE tests, namely, undesired coupling of the probe to external electric fields produced by knock-off electrons. Such a noise response was not anticipated, and it is unfortunate that the JADE circuits happened to be assembled in a manner which emphasized this response.